

**INTERFEROMETRIC CO OBSERVATIONS OF THE ULTRALUMINOUS IRAS
GALAXIES ARP 220, IC 694/NGC 3690, NGC 6240, and NGC 7469¹**

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ABSTRACT. High resolution CO observations of the IRAS galaxies Arp 220, IC 694/NGC 3690, NGC 6240 and NGC 7469 have been made with the Millimeter Wave Interferometer of the Owens Valley Radio Observatory. These yield spatial information on scales of 1 to 5 kpc and allow the separation of compact condensations from the more extended emission in the galaxies. In the case of the obviously interacting system IC 694/NGC 3690 the contributions of each component can be discerned. For that galaxy, and also for Arp 220, the unusually high luminosities may be produced by non-thermal processes rather than by intense bursts of star formation.

1. INTRODUCTION

IRAS observations have shown that the galaxies Arp 220, IC 694/NGC 3690, NGC 6240 and NGC 7469 are all extremely luminous with $L_{\text{FIR}} > 10^{11} L_{\odot}$ (Sanders and Mirabel 1985). The molecular gas masses, $M(\text{H}_2)$, derived from single dish measurements (Sanders and Mirabel 1985) are considerably in excess of $10^9 M_{\odot}$. In addition, the ratio $L_{\text{FIR}}/M(\text{H}_2)$, which can be interpreted as an indicator of star formation efficiency (Sanders *et al.* 1986a), is significantly enhanced. A comparison of the properties of these four galaxies with those of the starburst galaxy M82 is presented in Table I.

TABLE I

| Galaxy | D^a (Mpc) | $M(\text{H}_2)^b$ ($10^{10} M_{\odot}$) | L_{FIR}^b ($10^{11} L_{\odot}$) | $L_{\text{FIR}}/M(\text{H}_2)^b$ (L_{\odot}/M_{\odot}) |
|----------------------|----------------|--|---|---|
| Arp220 | 77 | 1.3 | 13.4 | 100 |
| NGC6240 | 101 | 1.99 | 5.3 | 26 |
| NGC7469 | 66 | 0.92 | 2.6 | 28 |
| NGC3690 } IC694 } | 48 | 0.73 | 5.3 | 72 |
| M82 | 3 | 0.17 | 0.2 | 12 |

Notes:

a) Assumes $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

b) From Sanders and Mirabel (1985) and Sanders *et al.* (1986a).

Although the presence of a significant quantity of molecular gas in these galaxies was discernible from the single dish CO observations, their 45" resolution was not sufficiently high to determine the distribution. Here we report 5" resolution, aperture synthesis CO maps of the four galaxies. These

¹ These results are presented in full by Scoville *et al.* (1987) and Sargent *et al.* (1986).

observations permit a study of the detailed structure of the molecular gas and the origins of the unusually high luminosities.

2. OBSERVATIONS AND RESULTS

Observations were made in the 2.6 mm CO line, using the Owens Valley Millimeter Wave Interferometer in May, 1986. For each galaxy, two configurations of the three 10.4 meter telescopes were employed, with spacings out to 80 m north-south and 65 m east-west. The shortest projected baseline was 10m, so that the interferometer is insensitive to structures greater than 30'' in size. A recently-completed, broad-band filterbank consisting of 32 channels, each 5 MHz wide, provided velocity coverage of 416 km s⁻¹, with 13 km s⁻¹ resolution. System temperatures were typically 300 K (SSB).

The resulting contour maps of integrated CO intensity for Arp 220, IC694/NGC3690, and NGC 7469 are shown in Figures 1, 2, and 3, respectively, overlaid on optical images of the galaxies. No emission was detected from NGC 6240 up to a level of 15% of the single dish flux, suggesting that the molecular gas in this galaxy is distributed on scales > 30'', rather than being confined to compact structures. In Arp 220 and NGC 7469, the CO emission is unresolved. This is also the case for each of the two compact regions detected in IC 694/NGC 3690. Upper limits to the diameters of the compact sources range from 1 to 2 kpc. Precise values, as well as the fraction of the single dish flux detected by the interferometer, F_i/F_s , are given in Table II. Average densities were calculated assuming a spherical distribution of gas and are also presented in Table II.

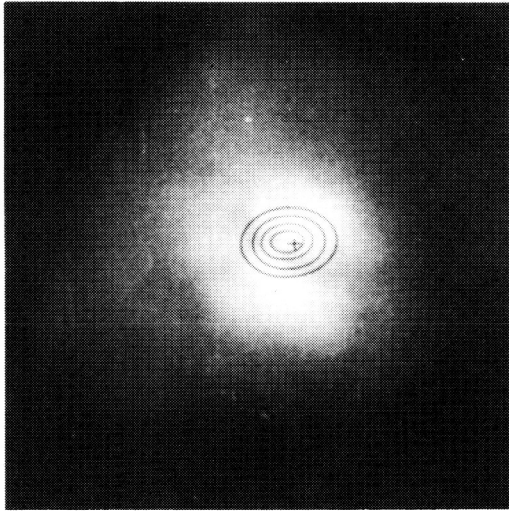


Figure 1: Contours of the integrated CO emission in Arp 220 superimposed on an optical photograph of the galaxy. Contour levels are spaced by 12 Jy/beam km s⁻¹, the lowest being 12 Jy/beam km s⁻¹.

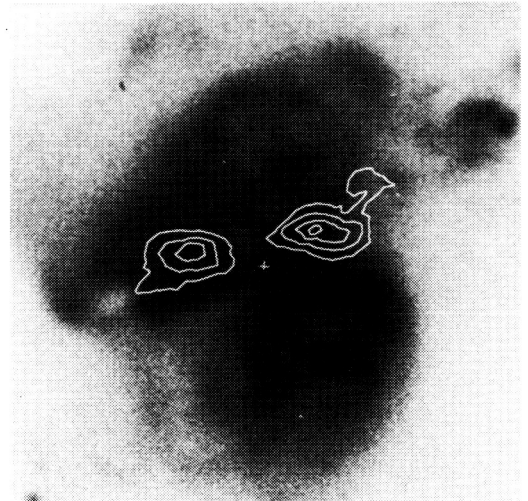


Figure 2: Contours of the integrated CO emission in Arp 299 (IC694-NGC3690) overlaid on an optical photograph of the galaxy. Contour levels begin at, and are spaced by, 10 Jy/beam km s⁻¹.

TABLE II

| Galaxy | Phase Center | | Beam | Scale (kpc) | F_i/F_s | $M(H_2)$ (10 ⁹ M _⊙) | N_{H_2} (cm ⁻³) |
|----------------------|--------------|------------|----------------|----------------|-----------|---|----------------------------------|
| | α(1950) | δ(1950) | | | | | |
| Arp220 | 15 32 46.92 | 23 40 07.9 | 6''.4 × 4''.0 | 1.4 | 0.7 | 9.1 | 130 |
| NGC6240 | 16 50 28.00 | 02 09 00.0 | 7''.6 × 6''.4 | 2.2 | < 0.15 | < 3 | < 10 |
| NGC7469 | 23 00 44.00 | 08 36 18.0 | 13''.7 × 6''.4 | 2.0 | 0.3 | 2.8 | 10 |
| NGC3690 } IC694 } | 11 25 42.60 | 58 50 14.0 | 8''.3 × 4''.8 | 1.0 | 0.5 | 3.2 | 70 |

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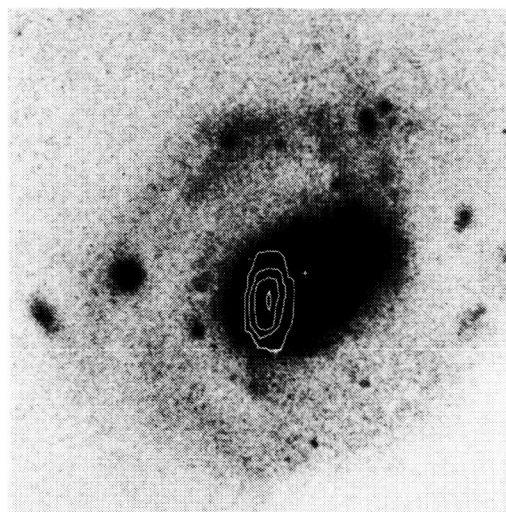


Figure 3: Contours of the integrated CO emission in NGC 7469 superimposed on an optical photograph of the galaxy. Contour levels are spaced by 8 Jy/beam km s^{-1} , the lowest being 8 Jy/beam km s^{-1} .

3. DISCUSSION

3.1. Arp 220

A substantial mass of molecular gas, $\sim 9 \times 10^9 M_{\odot}$, is concentrated in a region of radius < 700 pc at the nucleus of Arp 220 (Figure 1). The minimum mean density is 130 cm^{-3} and the ratio $L_{\text{FIR}}/M(\text{H}_2)$ is $100 L_{\odot}/M_{\odot}$. The star formation rate could be considerably enhanced as a result of an increased frequency of cloud–cloud collisions (cf. Scoville, Sanders and Clemens 1986), and the unusually high luminosity could be attributable to an intense burst of star formation (cf. Reike *et al.* 1985). However, it has recently been discovered that the spatial extents of the $20 \mu\text{m}$ and radio continuum emission are comparable, and less than $1.5''$ (Becklin 1986). This extreme concentration of the infrared and radio emission, the fact that the $\text{Br } \alpha$ emission is both unusually broad (de Poy 1986) and much weaker than expected if the luminosity is the result of high mass star formation (Beck, Turner and Ho 1986), the compact, dense molecular core, and the uncommonly high value of $L_{\text{FIR}}/M(\text{H}_2)$, provide compelling evidence that the energy in Arp 220 derives from non–thermal processes.

3.2. IC 694/NGC 3690

The interacting system Arp 299 comprises the galaxies IC 694 and NGC 3690. In the interferometer maps, two compact CO components were detected (see Figure 2), each of mass $\sim 1.4 \times 10^9 M_{\odot}$. The eastern component coincides with the nucleus of IC 694 (Telesco, Decher and Gatley 1985) where there is an unresolved, flat spectrum radio source, termed A by Gehrz, Sramck, and Weedman (1983); the western component spans their compact radio components C and C', which span the region where IC 694 and NGC 3690 overlap. Although CO is known to be present at the nucleus of NGC 3690 (Sanders *et al.* 1986b), no emission was detected by the interferometer, indicating that there the molecular gas must be distributed on scales greater than $30''$.

Observations at 60 and $100 \mu\text{m}$, at $20''$ and $30''$ resolution respectively (Harper 1984), show that about 75% of the total luminosity from Arp 299 arises from the nucleus of IC 694. If the luminosity source is as concentrated as the CO, $L_{\text{FIR}}/M(\text{H}_2)$ is $\sim 280 L_{\odot}/M_{\odot}$. The H_2 mass in a $16''$ region centered on this

nucleus is $\sim 2.4 \times 10^9 M_{\odot}$ (Sanders *et al.* 1986b), leading to $L_{\text{FIR}}/M(\text{H}_2) = 150 L_{\odot}/M_{\odot}$. These ratios are considerably greater than the values for the Milky Way, ~ 3 , and for starburst galaxies, $\sim 20 L_{\odot}/M_{\odot}$ (Sanders *et al.* 1986a, Scoville and Good 1986, Young *et al.* 1986). Taken together with the presence of the flat-spectrum radio source at the nucleus, these results strongly suggest that the source of energy in IC 694 may well be nonthermal. By contrast the ratio $L_{\text{FIR}}/M(\text{H}_2)$ for the remainder of the Arp 299 complex is between 40 and 70 L_{\odot}/M_{\odot} , indicating that the energy source here is probably massive star formation.

The effect of the interaction between IC694 and NGC3690 appears to have been to channel a substantial mass into the nucleus of IC 694, thereby producing an unusual energy source, probably fuelled by non-thermal processes. It has also induced increased density and, by implication, enhanced star forming activity in the region of overlap between the two galaxies.

3.3. NGC 7469

NGC 7469 is a type 1 Seyfert galaxy. From Figure 3, it is evident that the one CO source detected is offset from the nucleus by about 8". Its mass, $2.8 \times 10^9 M_{\odot}$, is approximately 30% of the total molecular gas mass measured by Sanders and Mirabel (1985). On the basis of $3.3 \mu\text{m}$ emission measures, Cutri *et al.* (1984) have suggested that star formation complexes may reside in a 2–8" annulus around the nucleus of the galaxy. Since the interferometer observations were somewhat limited, the resolution here is not optimal and the precise location and extent of the CO emission region is not well-determined. However, it is tempting to speculate that it represents the densest part of such an annulus, perhaps similar to that found around another Seyfert nucleus, NGC 1068 (Myers and Scoville 1986).

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DISCUSSION

A. S. Wilson. I'm a little puzzled by the offset of the CO emission from the nucleus of NGC 7469. The centimetric radio continuum and circumnuclear optical line emission center very well on the nucleus. Could atmospheric effects be responsible? It would be valuable if you could directly measure the relative positions of the CO and the radio continuum in your data.

Sargent. Our observations of NGC 7469 were somewhat limited so that the exact size and location of the compact CO region cannot be determined. It is possible that we have detected only the densest part of an annulus of gas centered on the nucleus. Higher sensitivity measures are needed to confirm this.

J. Carlstrom. Do you see any 3 mm continuum emission from these galaxies?

Sargent. We have not yet searched for continuum emission from the galaxies, although such a measurement might permit a more accurate determination of the CO offset from the nucleus.